U. S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Weather Service

NOAA Technical Memorandum NWS SR-66

IMPROVED BAROTROPIC HURRICANE TRACK PREDICTION BY ADJUSTMENT OF THE INITIAL WIND FIELD

Arthur C. Pike

SOUTHERN REGION HEADQUARTERS
SCIENTIFIC SERVICES DIVISION
FORT WORTH, TEXAS
July 1972

IMPROVED BAROTROPIC HURRICANE TRACK PREDICTION BY ADJUSTMENT OF THE INITIAL WIND FIELD

Arthur C. Pike, National Hurricane Center, Miami, Florida

ABSTRACT

Experiments are made using the Sanders integrated barotropic (Sanbar) model to forecast 24 selected 72-hour tropical cyclone tracks from the 1971 hurricane season. The initial wind field of each storm is regarded as the sum of a circularly-symmetric disturbance and a steering flow. Significant improvement in average forecast track accuracy is obtained when this steering flow is made uniform and equal to the observed initial storm motion. Best results are obtained, as expected, when the initial position and motion are obtained from best-track, post-analysis data. However, even operational initial conditions are shown to be of sufficient accuracy to improve the forecast.

1. INTRODUCTION

Since late 1970, a filtered barotropic prediction model operating on winds averaged with respect to mass through the troposphere has been in operational use at the National Hurricane Center (NHC). This model, originally designed by Sanders and Burpee (1968) and popularly termed "Sanbar", has been used to predict tropical cyclone tracks by the following of minimum stream function and maximum vorticity centers. Computations have been made on a Mercator projection grid of mesh length 1.5 degrees of longitude and extending from the equator to latitude 55°N and from longitude 36.5°W to 123.5°W. A time step of 30 minutes has been used and the forecasts have generally been made out to 72 hr.

In operational practice during the past two years, the pressure-depth over which the initial wind observations have been averaged has varied from 1000-400mb to 1000-100mb. On account of large oceanic regions with no routine upper wind soundings, 44 bogus mean winds have been used to supplement actual observations; see figure 1 for an illustration of their location. These winds have so far been obtained by a subjective analysis of the mean wind field as defined by the real data. Both real and bogus winds then form the basis for an objective analysis based on the work of Eddy (1967) which produces a wind field specified at the grid points. See section 2 for a description of how tropical storms are introduced into this analysis.

Once the initial winds have been specified, their non-divergent part is obtained by relaxing for the stream function ψ in the interior of the grid by means of

$$\nabla^2\psi = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} + \frac{u \tan\phi}{R_E} \qquad (1)$$

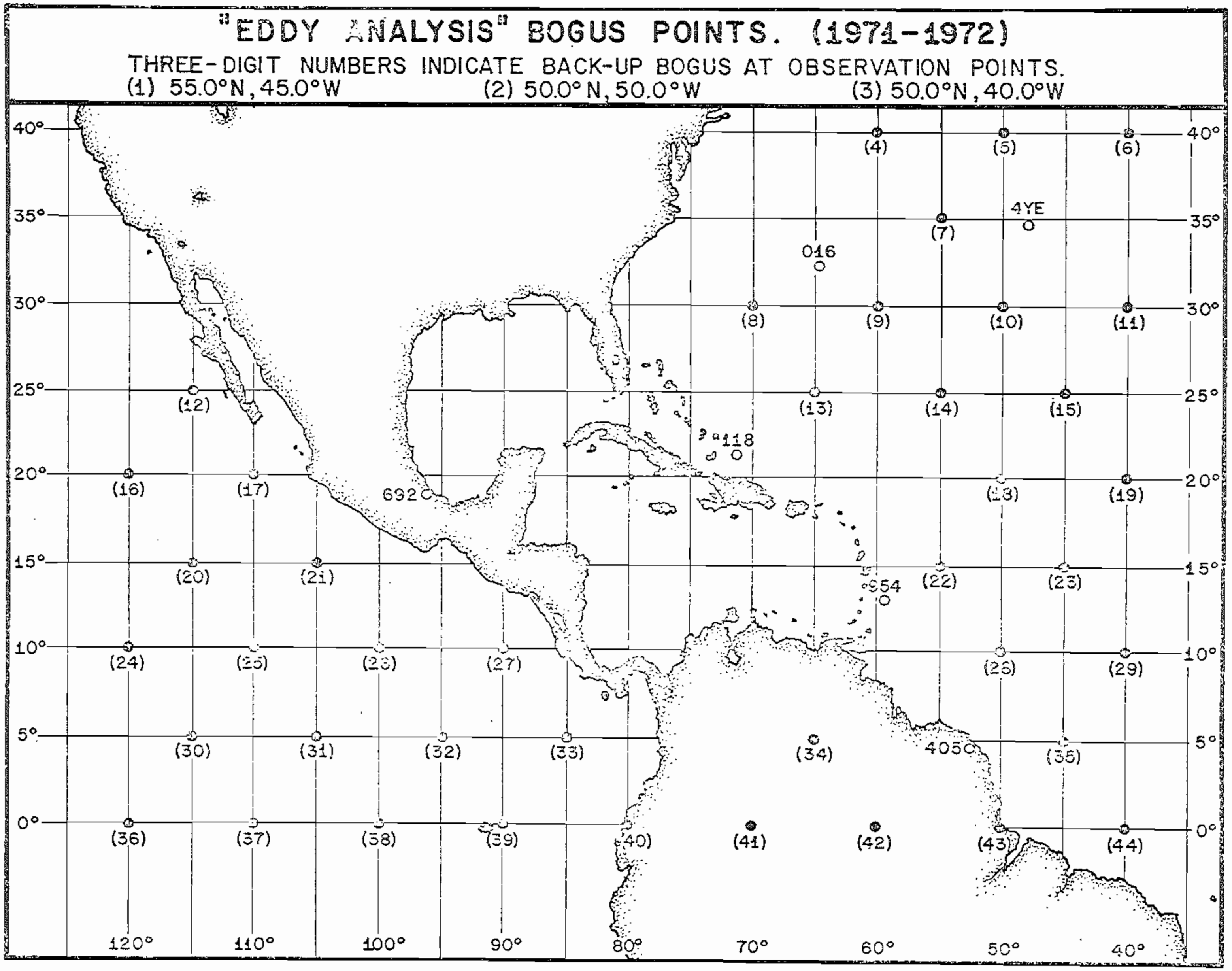

Figure 1. Bogus wind points for Eddy objective analysis.

where u and v are respectively the eastward and northward components of motion, ϕ is the latitude and R_E is the radius of the earth. Neumann boundary conditions, specifying the wind component parallel to the boundary, are used. The simple barotropic vorticity equation may then be used to predict ψ :

$$(\nabla^2 - M) \frac{\partial\psi}{\partial t} = J(f + \nabla^2\psi, \psi) \tag{2}$$

see Haltiner (1971), section 6.1. The horizontal Laplacian operator is denoted by ∇^2 , M is the Helmholtz coefficient, $\frac{\partial}{\partial t}$ is the local time derivative, f is the variable Conolis parameter, and J represents the Jacobian. A storm center may be identified with a local minimum in ψ or maximum in $\nabla^2\psi$; in practice, the average position between the two extremes is used. If a ψ-minimum cannot be found, the $\nabla^2\psi$-maximum, which is more persistent, is used alone.

Experience with the Sanbar model during the 1971 Atlantic hurricane season revealed a curious error pattern. At the 12 and 24 hour forecast verification times the Sanbar's performance was definitely worse than that of the two competing statistical forecast methods. Descriptions of these two may be found in Miller, Hill and Chase (1968) for the "NHC-67" method and in Hope and Neumann (1970) for the "Hurran" method. In contrast, at 48 and 72 hour the Sanbar method clearly outperformed the statistical models and at 72 hr actually did better, on the average, than the official forecasts prepared by hurricane specialists. See figure 2 for a graphic display of the comparative displacement errors.

It was thought that one major difference between the Sanbar and both statistical methods might explain the relatively poor showing of the Sanbar at short forecast intervals. The statistical models rely heavily on persistence of past motion for their short-range predictions. In contrast, the initial motion forecast by the Sanbar in 1971 depended completely on the

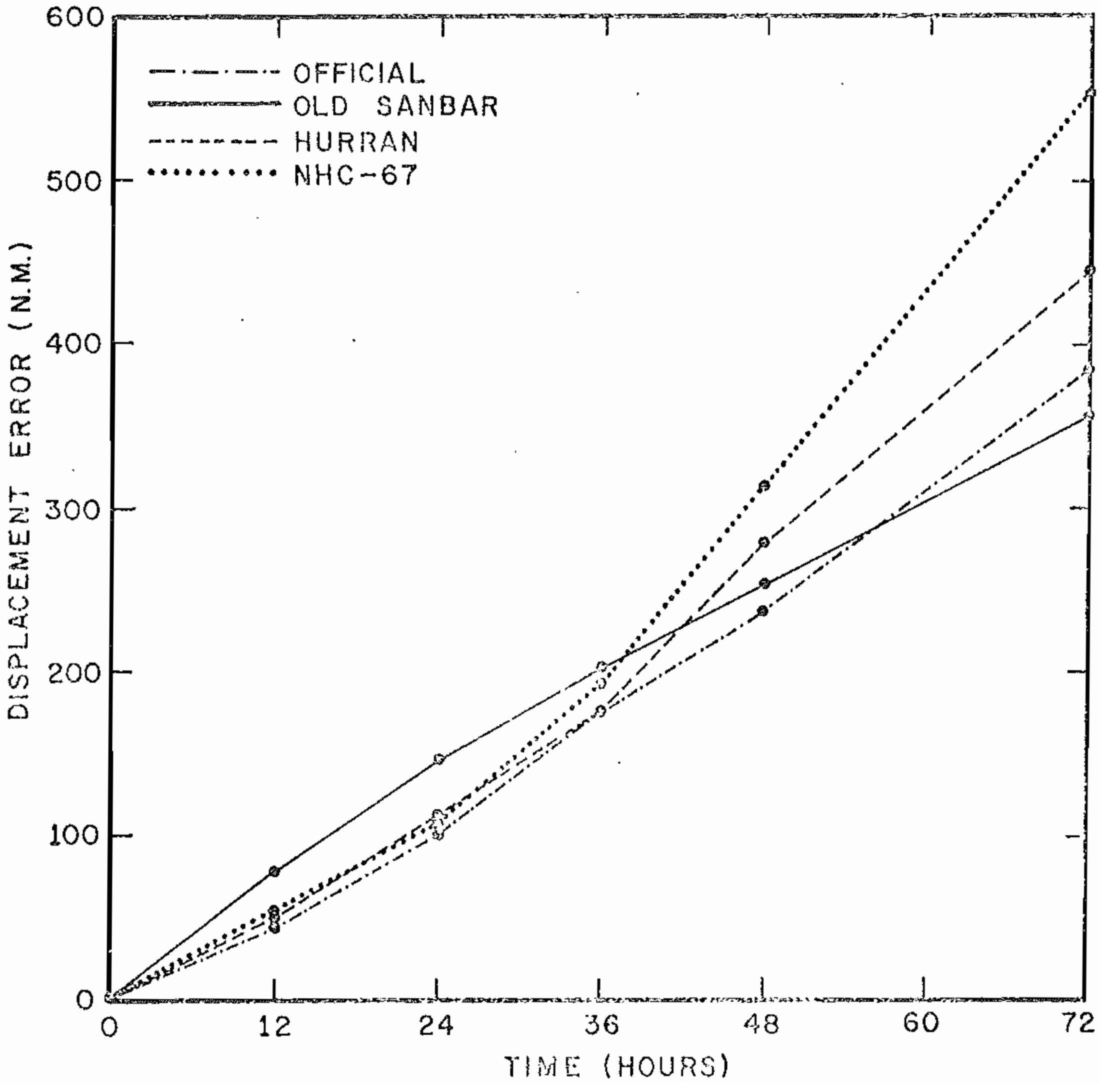

Figure 2. Comparative average displacement errors for all offical and objective forecasts, 1971 Atlantic hurricane season.

steering component of the wind field that happened to be produced by the Eddy objective analysis in the hurricane region. A simple method requiring the initial model steering to be equal to the observed storm motion will be discussed in section 2.

2. MODIFICATION OF THE INITIAL WIND FIELD

The pioneer work on improving the initial data for a dynamical prediction model to reflect observed storm motion is that of Jones (1964). He dealt with stream-function fields produced from those of observed geopotential heights by means of a balance equation. Stream-function data at several levels, after subtraction of a circularly-symmetric hurricane vortex, were averaged with respect to pressure to produce a mean steering flow. An assumption was made that the components of the steering velocity were related by multiple linear regression to stream function values at grid points within a limited region centered on the storm. It was then possible to modify these values to produce the required initial steering, with the constraint that the variance between the modified and unmodified stream functions be minimized.

This technique was tried using mean-tropospheric stream function data computed from 1000-100mb wind observations and bogus at 1200GMT, 12 Sept. 1971. Three tropical storms: Edith, Ginger and Heidi, were in existence at this time. In contrast to Jones's procedure of removing storm vortexes from the wind field, they were retained in this experiment. Storm intensities, as measured by maximum relative vorticity, were kept nearly intact through the stream function modification. However, negative absolute vorticities were produced on the boundary of the adjustment region. On account of this undesirable feature, it was decided to avoid stream-function adjustment by dealing with the initial wind field itself, including any storm vortexes.

The wind-field adjustment was made in the Eddy objective analysis routine. Originally, this analysis had been performed on station and bogus-point data after an idealized, circularly-symmetric vortex had been subtracted from each storm area. The speed field of this vortex is given by

$$v_\theta = 0.72 v_{max} \left[\sin \left\{ \pi \left(\frac{r}{r_m} \right)^{\left(\frac{\ln 0.5}{\ln (r_e/r_m)} \right)} \right\} \right]^{1.5} \tag{3}$$

where v_θ is the symmetric tangential wind speed, v_{max} is the maximum observed storm wind speed, r is the distance from the storm center to the point in question, r_m is the maximum storm influence distance and r_e is the radius of maximum v_θ. Note that $v_\theta(r=0) = v_\theta(r=r_m) = 0$. After the Eddy analysis had produced grid-point steering winds, the vortex defined by (3) was added back in.

This procedure has been modified at its two critical points, the subtraction of the vortex and its re-addition. Let us define $\vec{v}$ as the total wind vector, $\vec{v}_s$ as the steering vector and $\vec{v}_\theta$ as the vortex vector with speed defined by (3). At $r < r_m$ from storm centers, the $\vec{v}_s$ resulting from the vortex subtraction is set equal to the observed motion $\vec{v}_{so}$. Over the same region, the $\vec{v}$ resulting from the re-addition of the vortex is set equal to the sum of the observed motion and the vortex vector, $\vec{v}_{so} + \vec{v}_\theta$. In Table I are listed for comparison the original and the modified procedures for determining the initial steering. Note that $\vec{v}_{so}$ is constant over $r < r_m$; all other $\vec{v}$'s are variable.

Table I: Comparative Storm Wind Field Procedures

Step in Eddy analysis at $r < r_m$	Original	Modified
A. Subtraction of storm vortex at observation and bogus points	$\vec{v}_s = \vec{v} - \vec{v}_\theta$	$\vec{v}_s = \vec{v}_{so}$
B. Re-addition of storm vortex at grid points.	$\vec{v} = \vec{v}_s$ (analyzed) $+ \vec{v}_\theta$	$\vec{v} = \vec{v}_{so} + \vec{v}_\theta$

Between steps A and B, the objective analysis of the whole steering field is performed in exactly the same way in both the original and the modified routines. No negative absolute vorticities have been found to result from the imposition of observed steering in this manner.

3. EXPERIMENTS WITH FORCED INITIAL STEERING

An experimental sample of 24 tropical storm and hurricane cases occurring at 15 different initial times during the 1971 Atlantic hurricane season was assembled; they are listed in Table II.

Table II: Data Sample for steering experiments

1971 Date and Time	Storms	1971 Date and Time	Storms
8 Sept./00Z	Edith, Fern	24 Sept./00Z	Ginger
10 Sept./12Z	Edith, Fern, Ginger	25 Sept./00Z	Ginger
11 Sept./00Z	Edith, Ginger	25 Sept./12Z	Ginger
12 Sept./12Z	Edith, Ginger, Heidi	28 Sept./12Z	Ginger
13 Sept./00Z	Edith, Ginger	29 Sept./12Z	Ginger
14 Sept./12Z	Edith, Ginger	16 Nov./12Z	Laura
15 Sept./12Z	Edith, Ginger	17 Nov./12Z	Laura
23 Sept./12Z	Ginger		

Operationally during the 1971 season, the Sanbar model with the original initial analysis routines was run for 21 of the above cases. Varying pressure depths were used for the vertical wind averaging. The Edith case on 14 Sept. and both the Fern cases were not run. For these 21 cases, the mean 24-hr displacement error was 170 naut. mi. compared with a 147 naut. mi. average for all 81 times the Sanbar model was run through 24 hr that year.

At first, a sub-sample of the above cases was analyzed. This group consisted of the seven storms beginning at 12 Sept./12Z, 15 Sept./12Z, 24 Sept./00Z and 29 Sept./12Z. As with all the other experimental cases of this paper, the initial winds were averaged over a 1000-100mb pressure depth in order to provide as non-divergent, and representative of the whole troposphere, an initial field as possible. This particular first sample was chosen for study since it had already been analyzed, using the same pressure depth, under operational conditions. It would be possible to compare forecasts made with initial analyses of routine quality with those depending on research analyses.

Figure 3 presents average position errors as a function of time for these seven cases using operational bogus. Note the marked improvement in forecast accuracy, at all times, when the initial steering is forced in. Even when operational initial position and motion are used, over the first 36 hr the position error is reduced by half when compared with the results of the original method. Introduction of best-track initial data reduces the errors further by an amount nearly independent of time, suggesting that initial position error is a more pervasive culprit than is initial motion error. A significant feature of figure 2 is that forced initial steering reduced forecast errors to levels below 1971 official errors. Substantial hope for improvement of actual hurricane track forecasts with the aid of this modified Sanbar technique is indicated.

For the forecast experiments of figure 4, research bogus has been used to obtain the initial wind fields in the same seven cases. The major difference between the operational and research bogus calculations is that the unmodified Sanbar forecasts are consistently better in the latter. Detailed checking of the operational bogus revealed some plainly impossible winds, particularly a few near storm centers. The research bogus had none of these. Curiously, the Sanbar forecasts with forced initial steering were not improved when research bogus replaced operational. In this case, any improper bogus wind near the storms would have been overridden by the model vortex plus steering. It seems that the quality of the research bogus well away from the storms was no better than that produced

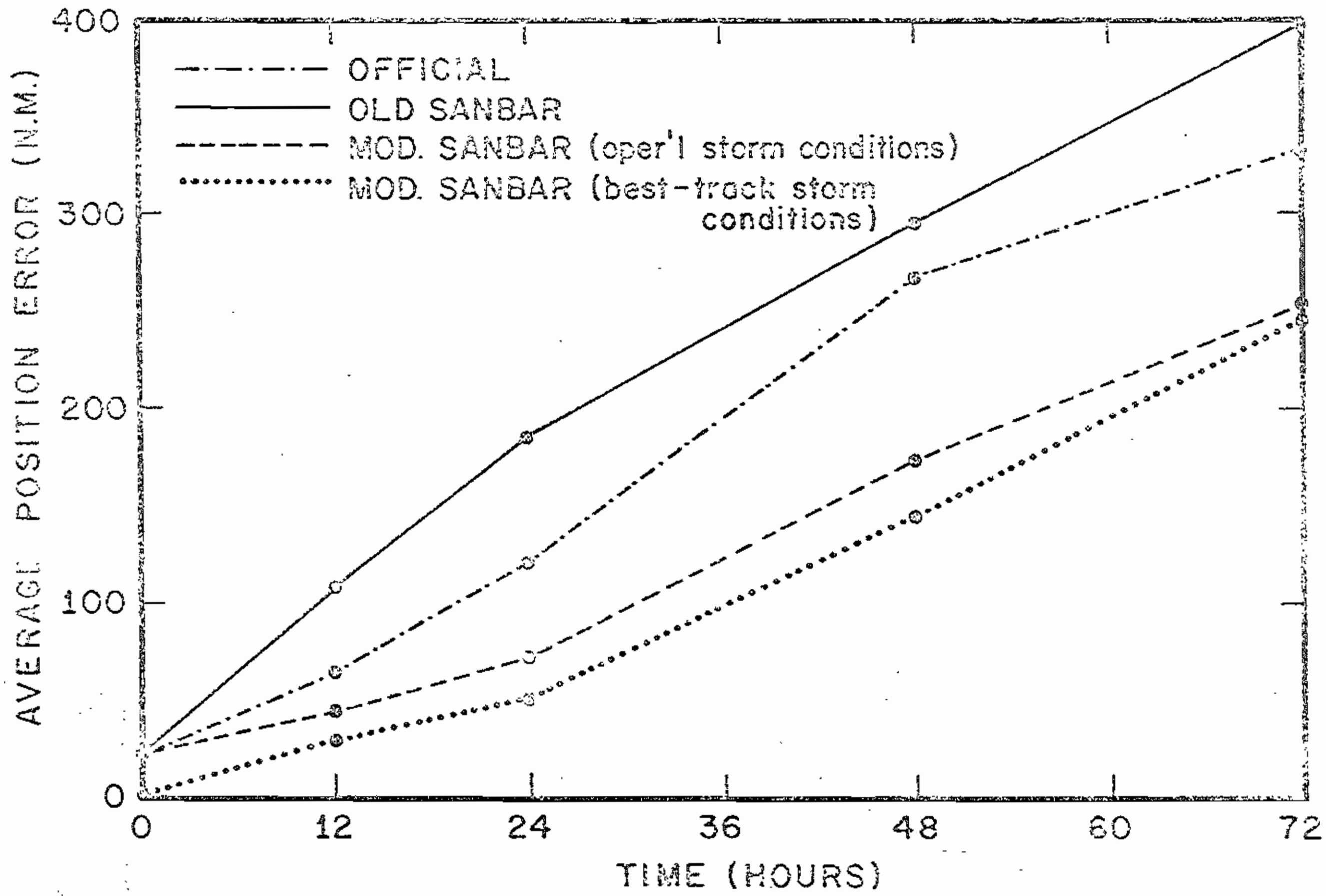

Figure 3. Average position errors for seven-case sample, operational bogus.

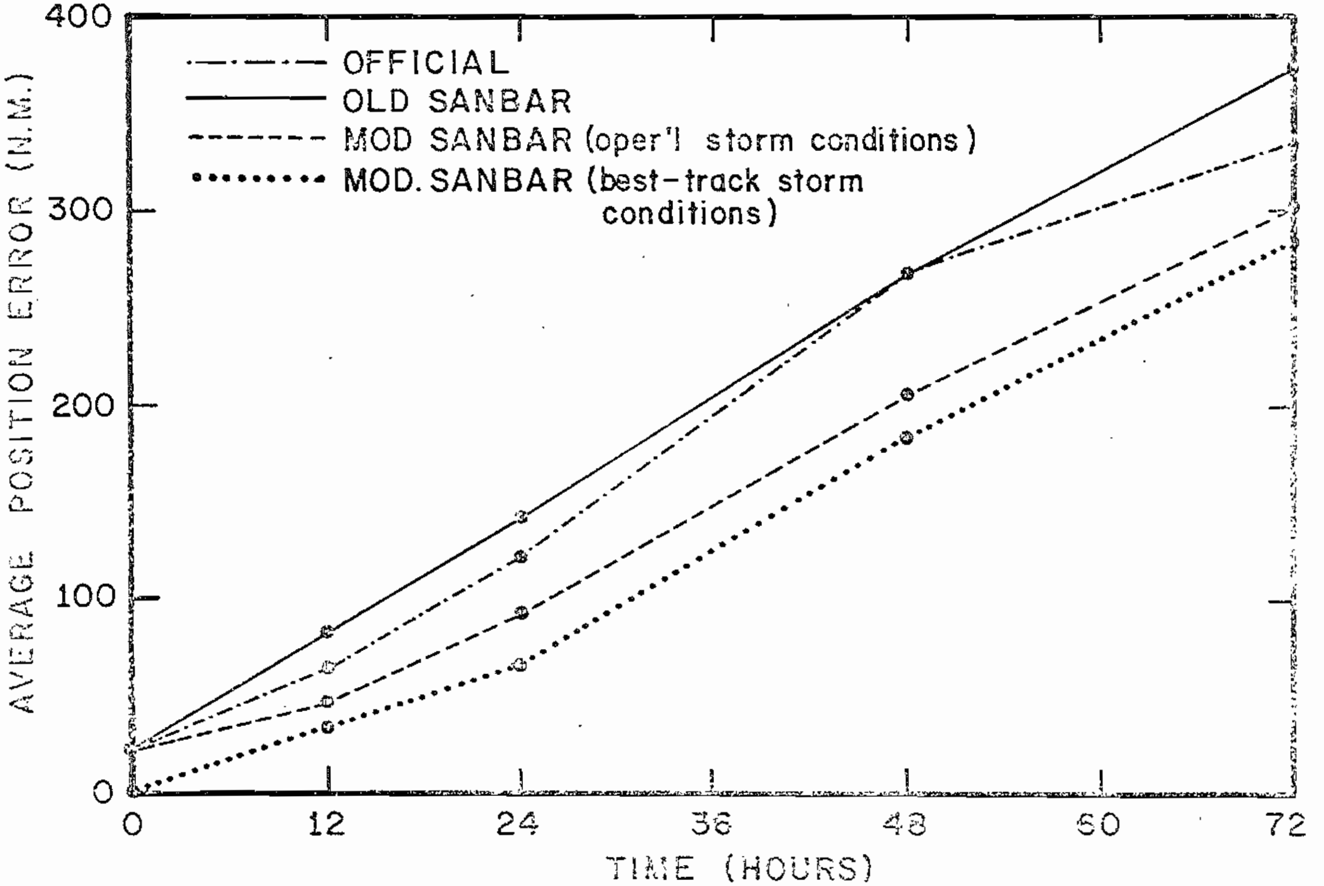

Figure 4. Same as Figure 3 but using a research bogus.

operationally. The forecast improvement resulting from the use of best-track initial storm conditions is of the same character described previously.

All 24 cases of Table II were included in the statistics of figure 5. Here, research bogus was used. Note that even the unmodified Sanbar forecasts are better than the official ones, on the average, at 48 and 72 hr. Forced initial steering produces a smaller reduction in average position error when this larger sample is considered. However, the reduction is consistent in time and exceeds 15 per cent in size at 12, 24 and 48 hr. This amount of improvement is sufficient to make the modified Sanbar forecasts of higher average quality than the official forecasts at all times. An increase in the accuracy of initial storm positioning would improve matters even further.

Forecasters are interested in the future direction and speed of a storm's motion as well as in its future location. The direction of motion is usually more crucial than the speed on account of the importance of prediction of the landfall point on a coast. During the 1971 hurricane season the utility of Sanbar forecasts was hindered by their marked left directional and slow speed biases. This situation has been confirmed by our calculations with the 24 case sample; during the first 24 hr with the unmodified Sanbar the directional bias was left 28 degrees and the speed bias was 21 per cent below observed. Introduction of forced initial steering reduced the directional bias to an insignificant left one degree for operational data and to zero for best-track data. The speed bias was only slightly reduced, to 18 per cent. It is clear that the problem of directional bias has been solved by our initial steering modification, but the slow early forecast speeds remain. Possible methods for increasing them will be discussed in the next section.

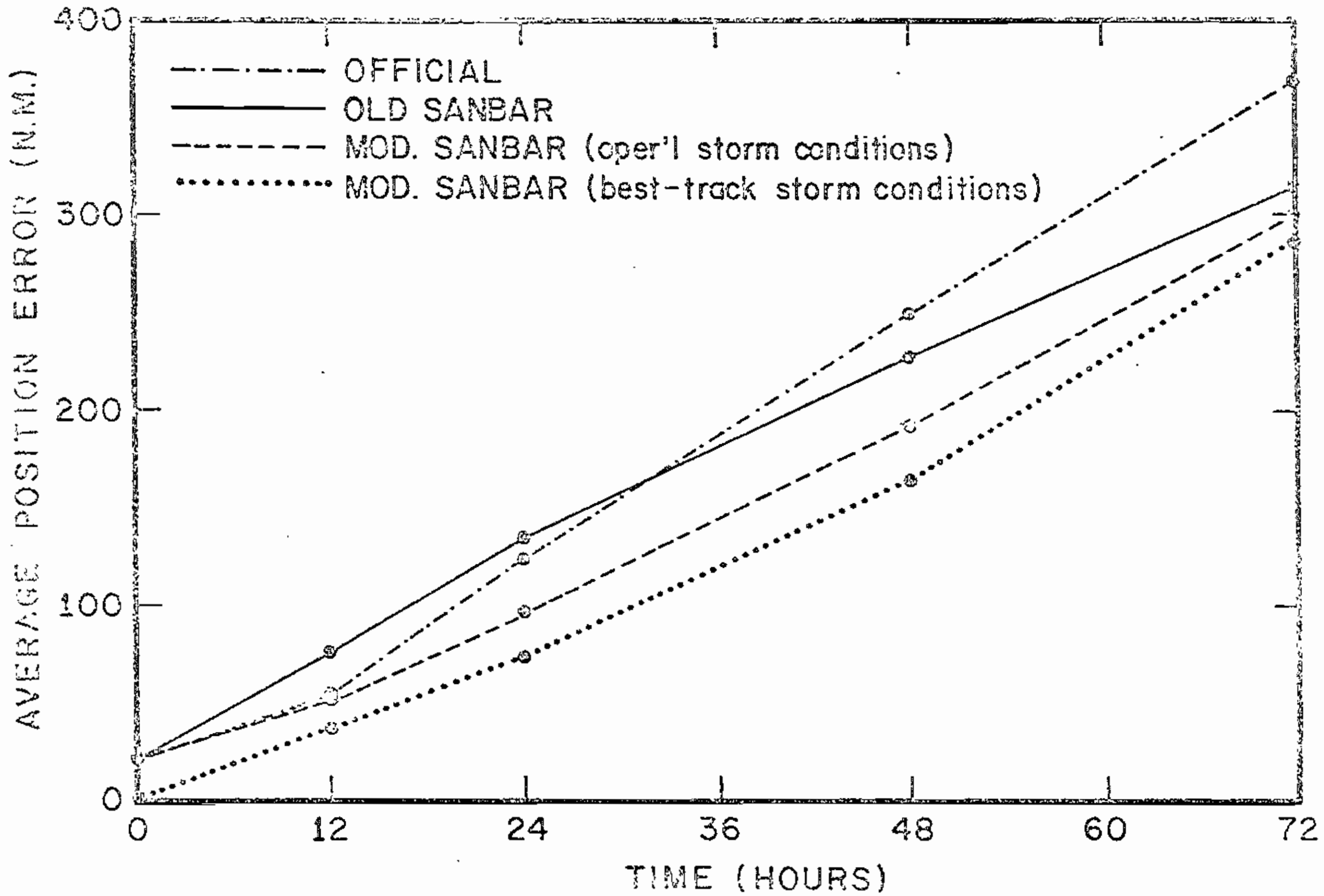

Figure 5. Average position errors for 24-case sample. research bogus.

4. POSSIBLE SOLUTIONS TO SLOW BIAS

Recall that the Sanbar forecast system applies the barotropic vorticity equation to a wind field integrated through the troposphere. Similar averaging of the equation yields a correlation term between wind velocity and absolute vorticity gradient which has so far been neglected. If the wind direction is assumed to be constant with pressure, p, and the wind speed to vary as $A(p)\overline{V}$ where $\overline{V}$ is the average speed, the correlation's influence may be included by multiplying the initial wind field by $\overline{A^2}$. This equivalent-barotropic effect is discussed in Haltiner (1971), section 6.1.

Introduction of the $\overline{A^2}$ factor, estimated at 1.25 in middle latitudes (Haltiner, op. cit.) and at between 1.05 and 1.15 in the summer tropics (F. Sanders, personal communication) was indicated to speed up the Sanbar. With $\overline{A^2} = 1.25$ and either operational or best-track initial storm data, the 24-case initial speed bias was reduced 6 per cent below observed. Since a larger $\overline{A^2}$ was not indicated, further speeding was achieved by setting the Helmholtz factor M in equation (2) to zero while using a more realistic $\overline{A^2} = 1.15$, for the tropics. In this case the computed average speed through 24 hr differed by less than one per cent from the observed.

A very undesirable side effect accompanied this resolution of initial slow bias. Figure 6 shows the comparative average position errors for the modified Sanbar for $\overline{A^2} = 1$, $\overline{A^2} = 1.25$, and $\overline{A^2} = 1.15$ with no Helmholtz factor. Best-track initial conditions were used. Note the progressive increase of error, especially at 48 and 72 hr, as the early slow bias is corrected. Analysis of the variation of the model's total kinetic energy with time revealed a tendency for a slow but steady increase in the majority of cases. Indeed, operational experience with Sanbar had indicated that the early

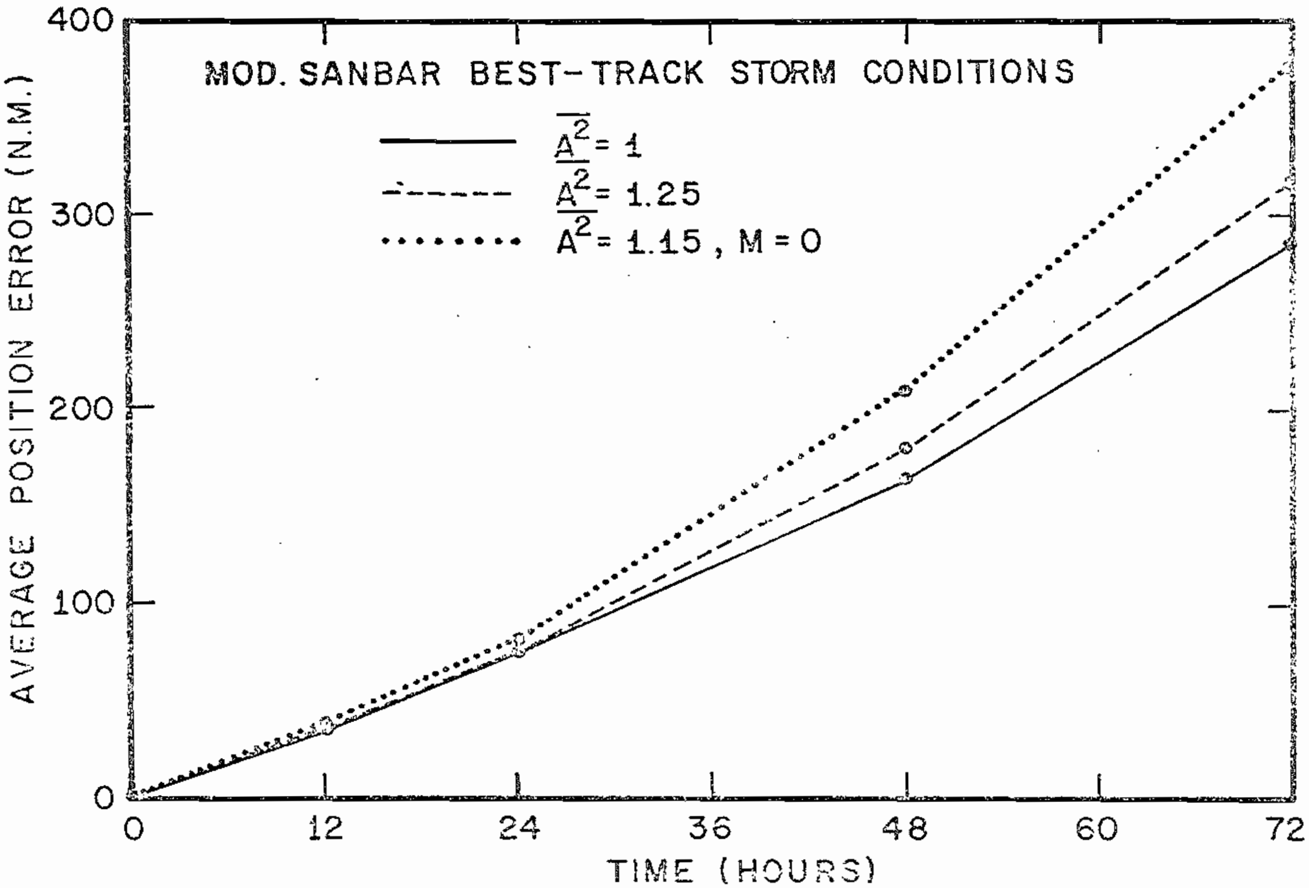

Figure 6. Response of Sanbar position errors to techniques which speed up initial storm motion.

slow bias did not persist. Apparently the kinetic energy, or momentum, variation in the model should be prevented when an initial speeding up is made, in order to avoid greater errors.

An attempt was made to conserve kinetic energy by introduction of the Arakawa Jacobian into equation (2); see Haltiner (1971) section 12.3. No significant difference from before, when the usual four-point Jacobian had been used, was obtained. Other more sophisticated Jacobians fared no better. It would seem that the non-conservative nature of the leapfrog time step and/or boundary effects were contributing to the kinetic energy changes. Further work is presently underway to resolve this problem, perhaps by a repeated, very small empirical correction to the stream function.

5. SUMMARY

The Sanders integrated barotropic model, Sanbar, has been studied in order to improve the accuracy of its hurricane track forecasts. Comparison of Sanbar prediction errors with those of statistical methods revealed poorer Sanbar performance at the early forecast times followed by better results beyond 36 hr. It was decided to include observed storm motion in the Sanbar initial wind field since the statistical models depended heavily on this information for their short-range forecasts. Significant improvement was obtained with this technique. Directional bias was eliminated but the slow early speed bias characteristic of Sanbar was only slightly reduced. Introduction of an equivalent-barotropic multiplier for the initial wind speeds did remove the speed bias but significantly increased average position errors at later times. Further calculations showed that the total kinetic energy of Sanbar tended to increase slowly but steadily with time, speeding up the storm movement unduly at later periods. When strict control of the kinetic energy has been effected, use of an equivalent-barotropic factor should properly resolve the speed bias.

6. ACKNOWLEDGEMENTS

The constant encouragement of Frederick Sanders has been essential to this study. Robert H. Simpson, director of the National Hurricane Center and Banner I. Miller, chief of its research and development group have allowed me ample time for careful work. The programming assistance, of Elbert C. Hill and Mildred A. Kirkland has been invaluable. Clark L. Smith performed the research analyses and bogus. Robert L. Carrodus and David Shields drafted the figures. I am grateful to Mariano A. Estoque for good advice.

REFERENCES

Eddy, A., 1967: "The Statistical Objective Analysis of Scalar Data Fields," Journal of Applied Meteorology, Vol. 6, No. 4, pp. 597-609.

Haltiner, G. J., 1971: Numerical Weather Prediction, John Wiley and Sons, Inc., New York, 317 pp.

Hope, J. R. and C. J. Neumann, 1970: "An Operational Technique for Relating the Movement of Existing Tropical Cyclones to Past Tracks," Monthly Weather Review, Vol. 98, No. 12, pp. 925-933.

Jones, R. W., 1964: "On Improving Initial Data for Numerical Forecasts of Hurricane Trajectories by the Steering Method," Journal of Applied Meteorology, Vol. 3, No. 3, pp. 277-284.

Miller, B. I., E. C. Hill and P. P. Chase, 1968: "Revised Technique for Forecasting Hurricane Motion by Statistical Methods," Monthly Weather Review, Vol. 96, No. 8, pp. 540-548.

Sanders, F. and R. W. Burpee, 1968: "Experiments in Hurricane Track Forecasting," Journal of Applied Meteorology, Vol. 7, No. 3, pp. 313-323.